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MEASURING TILT WITH AN AUTOMATIC LEVEL

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BIOGRAPHICAL SKETCH

Kenneth Robertson is a research physicist with the Engineer Topographic Laboratories where he is concerned with the development of advanced surveying instruments and techniques. While at ETL, he has developed a falling body device to measure absolute gravity, a laser alignment instrument for use on dams, a non-contact optical method of measuring velocity, a means of measuring angles without circles or encoders, and the present technique of measuring tilt. Mr. Robertson also developed the ratio techniques used in dam monitoring with distance measuring instruments. He is a 1951 graduate of Indiana University.

ABSTRACT

The long-term or short-term tilt of structures such as locks or dams may be measured with an automatic level which has been temporarily modified for the purpose. The modifications consist of the addition of an autocollimating eyepiece and an optical vernier. A calibration mirror is also required for the measurement of long-term tilt. Accuracies of 1 to 5 seconds of tilt may be obtained.

INTRODUCTION

Large structures such as locks and dams need to be continuously evaluated to insure their structural safety and stability. Such evaluations should be supported by programs of instrumentation that will provide a means of detecting structural distress or abnormal operating conditions. One vital piece of information is the degree to which a structure tilts or bends under load.

Normally these measurements are made through the installation of a plumb line or an inverted plumb line or an optical plummet. Tilt is inferred from the displacement of the plumb bob and the length of the plumb line. Measurements of displacement at intermediate points along the plumb line give information regarding bending of the structure. Plumb lines, however, suffer from some serious drawbacks. They are expensive. Installation in a single monolith may cost as much as $50,000, and it must be installed during construction of the dam. Because of this only one or two monoliths in a dam are usually equipped. In

addition, the plumb lines lack sensitivity near their points of suspension, necessitating the use of an inverted plumb line. To monitor bending in a monolith, both types may be required. Finally, plumb lines lack sensitivity on shorter structures. A deflection of 10 seconds in a dam 20 meters high gives a deflection of only 0.1 millimeters.

The purpose of this paper is to describe an instrument which measures tilt directly. The instrument consists of a Zeiss Ni 2 Automatic Level, an autocollimating eyepiece, an optical vernier, and a calibration mirror. Long-term measurements of tilt are made of permanently mounted mirrors. These are attached to each vertical surface where a measurement of tilt is required. As the vertical surface tilts, the mirror follows the movement and the instrument is designed to detect these small deflections. For short-term measurements, such as those encountered during the fill, empty cycle in a lock, a tripod mounted mirror may be used.

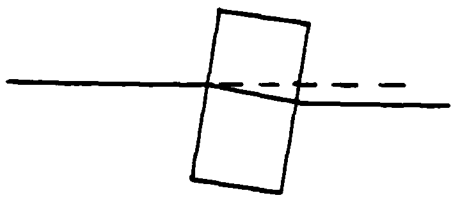
The instrument accuracy for measurements is about one second of arc over a range of plus or minus 7.5 minutes of arc. Using the qualities of the pendulum compensator in the level and a calibration mirror, all measurements are referred directly to the local gravity vector. Because of the calibration, the instrument is virtually free of the effects of drift in the compensator. While not being used to measure tilt, the automatic level may be returned to its normal function.

THE LEVEL AND AUTOCOLLIMATING EYEPIECE

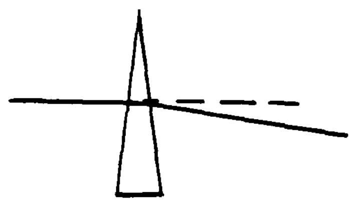
The autocollimator is a device which is widely used in optical tooling for measuring small angles. It consists of a small telescope which has been focused at infinity. At the focal plane of the eyepiece of this telescope, a crosshair reticle is placed. A small light source is then added to illuminate the reticle and the image of the reticle is projected along a collimated beam from the telescope. If the beam strikes a mirror which has been placed in position perpendicular to the axis of the telescope, the image of the crosshair will be reflected back into the telescope and will come to a focus at the same spot as the original crosshair. If the mirror is then tilted slightly, an observer looking through the autocollimating eyepiece would see the image of the crosshair slightly displaced from the original crosshair. The amount of displacement is a sensitive measure of the angular tilt of the mirror. Instruments of this nature have been in use in the laboratory and in the optical tooling industry for many years.

An autocollimating eyepiece for the Zeiss Ni 2 level will convert the level to an autocollimator. The

eyepiece contains an additional reticle which enables the user to measure the displacement of the crosshair and thus the angle of tilt of the mirror. The reticle is graduated in 10 second intervals and estimations may be made to two or three seconds of arc. For finer readings, an optical vernier is added. The vernier consists of a thin wedge of glass which bends the line of sight in the direction opposite the point of the wedge. This should not be confused with the parallel plate attachment for the level which is used as a vernier when a normal leveling course is being run. The parallel plate attachment, as the name implies, uses a thick plate of glass with parallel sides. The plate is tilted in the optical path to displace the line of sight, but without bending it through an angle. The figure shows the difference between the two attachments.



PARALLEL PLATE ATTACHMENT



OPTICAL WEDGE

If the optical wedge is rotated, the line of sight may be deviated up, down, right, or left. An observer viewing the image of the crosshair reflected from a mirror and passing through the optical wedge would see the crosshair move in a circle as the wedge was rotated. Left, right motions of the crosshair may be disregarded and only the up, down motions used. The wedge may be calibrated so that deviation of the line of sight is equated to rotation of the wedge. In use, the wedge is rotated until the crosshair image is brought into coincidence with one of the reticle graduations. The rotation of the wedge needed to accomplish this is then an accurate measure of the difference in seconds between the image and the reticle line. The deflection of the crosshair image and the tilt of the mirror causing the deflection may now be read to approximately 0.5 seconds of arc using the optical wedge.

Each time the instrument is used to measure the tilt of a mirror the line of sight of the instrument must lie along the same plane. Because an automatic level is the telescope of the autocollimator, the line of sight lies in the horizontal plane and all measurements are referred to the horizontal.

Although the compensator in an automatic level will maintain a reproducible line of sight over an extended period, this line may not be perfectly horizontal. This is the reason that foresights and backsights need

to be balanced in high order leveling. For the purpose of measuring tilt it is necessary to determine the departure of the line of sight from the horizontal because the compensator may change over long periods or be disturbed by rough handling. In addition, the autocollimating reticle may not be placed in exactly the same position each time, further disturbing the horizontal reference of the readings. Thus it is necessary to have a simple means of calibration for the instrument which may be used immediately before and after a day's set of readings.

THE CALIBRATION MIRROR

This is provided by means of a special mirror. If it were possible to make this mirror perfectly vertical, a reading of the mirror by the instrument should show zero tilt. If it does not, it is because of the errors in the compensator and in the positioning of the autocollimator reticle. Because the mirror is vertical, the total error may be read directly from the reticle and optical vernier, and the results applied as a correction to subsequent readings.

The calibration mirror is one which is ground and polished to have faces which are parallel to within 0.5 seconds of arc. This mirror is mounted to a tribach in an approximately vertical position and a reading of tilt is made of one face with the instrument. Without moving the mirror the instrument is then used to make a reading of the other face. If the mirror were perfectly vertical both readings would be the same even if the instrument line of sight were not horizontal, and the difference of the readings from zero would be the error in the instrument. If the mirror were not vertical, the two readings would not agree, but the mean of the two would be the error of the instrument. This calibration takes less than 20 minutes to perform and should be done at the beginning and end of each day's readings to check for drift. Typically the difference will be less than 2 seconds and the mean of the two sets may be used to correct the intermediate readings of the mirrors monitoring tilt of the structure.

A set of measurements at a dam would then consist of an initial calibration with the calibration mirror, a reading of each of the mirrors mounted in the structure, and then a final set of calibration readings. Each calibration takes about 20 minutes and the reading of each mirror in the structure takes about 5 minutes. Accuracy of the reading of the instrument is about 2 seconds of arc.

STRUCTURE MIRRORS

An essential part of the tilt monitoring system is the

structure mirror. This must perform several functions. The mirror must be mounted in such a manner that it accurately follows the tilt of the structure, the mount must not distort the mirror so than an unclear image is seen in the autocollimator, and the mount must provide a means of setting the mirror to an almost vertical initial position so that the image of the crosshair will be near the center of the range of the instrument.

Providing for these requirements has proved to be the most difficult part of the work. Each mirror was first affixed to an aluminum plate using a slow curing epoxy cement. Most of the mirrors treated in this way gave good results, but a few were strained enough by the mounting process to return fuzzy images in the autocollimator.

Next, a backing plate for each mirror was attached to the wall of a gallery using a structural epoxy cement and the epoxy was allowed to cure for two weeks. Finally each plate with its mirror was mounted to a backing plate using a three point adjustable suspension under spring tension. The suspension was then adjusted using the autocollimator to bring the mirror into an approximately vertical position. An additional two weeks was allowed for the strain in the suspension to be relieved and the first set of readings was taken. Each mirror assembly was provided with a protective cover.

RESULTS

Two types of tests have been performed with the tilt measuring system. The first test was in the gallery of Philpott Dam near Roanoke, VA. Here, six mirrors were mounted in a gallery, four on the downstream wall and two on the upstream wall. All were in the same monolith so that the tilt in each mirror should be the same, and the characteristics of the mirror mounts could be tested. Surprisingly, the mirror mounts required three months to stabilize, due perhaps to the cool temperatures encountered in the gallery.

After the mounts had stabilized, readings showed a steady downstream tilt for the next three months with a total tilt of about 30 seconds of arc. It is believed that the measurements represent the true tilt or bending of the structure with an accuracy of $\pm$ 5 arc seconds. This accuracy figure is derived from the agreement of the four mirrors on the downstream wall, and from the two mirrors on the upstream wall which give values of the same magnitude but of different direction. If the downstream mirrors are tilting with their upper edges away from the instrument, then the upstream mirrors should show their upper edges tilting towards the instrument.

A second type of test was performed at Holt Lock and Dam in the Mobile District. Here it was desired to measure the tilt of a lock wall during the fill, empty cycle. The instrument and the calibration mirror were set up on tripods so that tilt of the lock wall would cause the calibration mirror to tilt in a like manner. Calibration was not required because relative values of tilt were to be measured over a short period of time without disturbing the instrument or mirror. A time of day near evening was picked to reduce the effect of temperature changes on the calibration mirror and tripod. In addition, an umbrella was used to shade the mirror. A tilt of 12 seconds of arc was measured between full and empty conditions of the lock. After emptying of the lock, less than one second of change was seen over the next several hours.

CONCLUSIONS

An instrument has been developed to monitor tilt in large structures. The instrument consists of an automatic level, an autocollimating eyepiece, an optical vernier, and a calibration mirror. Also required is a wall mounted mirror which will follow the tilt of the structure. Tests of the instrument reveal that measurements of tilt may be made with an accuracy approaching one second of arc. Work is continuing to improve the stability of mirror mounts to be used in permanent installations, but measurements with an accuracy of 5 arc seconds are presently possible. Cost of the instrument is about $4000 plus the cost of the Zeiss Ni 2 Automatic Level. In addition each monolith to be monitored should have two mirrors installed, one on the upstream and one on the downstream wall of a gallery. The cost would be approximately $300 per monolith. A complete report on this work is in preparation.

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